Strangeness and Charm Signatures of the Quark-Gluon Plasma

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Abstract. Strangeness, charmonium and open charm yields in relativistic nucleus-nucleus collisions are considered within statistical model approach as potential signals of the quark-gluon plasma.

I. Introduction

The present status of the quark-qluon plasma (QGP) in nucleus–nucleus (A+A) collisions is somewhat uncertain. Experimental data for A+A collisions with truly heavy beams have become available: Au+Au at 11 A·GeV at the BNL AGS and Pb+Pb at 158 A·GeV at the CERN SPS [1]. A systematic analysis of these data could yield clues to whether a short-lived phase with quark and gluon constituents, the QGP, exists during the hot and dense stage of these reactions. This question, whether the QGP is already produced with the currently operating heavy ion accelerators, is right now vigorously debated. There are also convincing hopes to find new reliable evidences of the QGP within a few years. The accelerators of a new generation RHIC BNL and LHC CERN will start soon to operate.

Since a long time [2] statistical models are used to describe hadron multiplicities in high energy collisions. Thermal hadron production models have been successfully used to fit the data on particle multiplicities in A+A collisions at the CERN SPS energies (see, e.g. [3, 4, 5]). Due to the large number of particles a grand canonical formulation is used for the modeling of high energy heavy ion collisions. Recently, an impressive success of the statistical model applied to hadron multiplicities in elementary $e^+ + e^-$, $p+p$ and $p+\bar{p}$ interactions at high energy was also reported [6]. However, in the latter case the use of a canonical formulation of the model, which assures the exact conservation of the conserved charges, is necessary (see, e.g., [7] and references therein).

The temperature parameter which characterizes the available phase space for the hadron production is found in these interactions to be 160–190 MeV [6]. It does not show any significant dependence on the type of reaction and on the collision energy (at the SPS energies and higher). This fact suggests the possibility to ascribe the observed statistical properties of hadron production systematics in elementary and nuclear collisions at high energies to the statistical nature of the hadronization process [6, 4, 8].

II. Strangeness Production

The enhanced production of strangeness was considered by many authors as a potential signal of QGP formation (see, e.g., Ref. [9]). The expectation was that strangeness production should rapidly increase when the energy transition region is crossed from below. The strangeness to pion ratio is indeed observed to increase in A+A collisions. It seems however that this is not a signal of the QGP. The low level of strangeness production in p+p interactions as compared to the strangeness yield in central A+A collisions, called strangeness enhancement, can be also understood to a large extent as due to the effect of the exact strangeness conservation. The canonical ensemble treatment of the strangeness conservation leads to the additional suppression factors imposed on the strange hadrons production in small systems created in p+p collisions [6, 7]. Another important point is that for the chemical freeze-out parameters, temperature T and baryonic chemical potential μ_b, found for the SPS energies the strangeness to entropy ratio is larger in the equilibrium HG than in the equilibrium QGP [5].

To estimate the strangeness to entropy ratio let us consider the quantity

$$R_s \equiv \frac{N_s + N_{\bar{s}}}{S} \,, \tag{1}$$

where N_s and $N_{\bar{s}}$ are the numbers of strange quarks and antiquarks, and S is the total entropy of the system. In the QGP we use the ideal gas approximation of massless u-, d-(anti)quarks and gluons, strange (anti)quarks with $m_s \cong 150$ MeV and (anti)charm quarks with $m_c \cong 1500$ MeV. For the HG state the values of N_s and $N_{\bar{s}}$ are calculated as a sum of all s and $\bar{s}$ inside hadrons, and S is the total HG entropy. The behaviour of R_s (1) for the HG and QGP is shown in Fig. 1 as a function of T for $\mu_B = 0$. In the wide range of $T = 200 \div 500$ MeV one finds an almost constant value of R_s in the QGP which is smaller than the corresponding quantity in the HG. The total

entropy as well as the total number of strange quarks and antiquarks are expected to be conserved approximately during the hadronization of QGP. This suggests that the value of R_s at the HG chemical freeze-out should be close to that in the equilibrium QGP and smaller than in the HG at chemical equilibrium. Therefore, the strangeness *suppression* in the HG would become a signal for the formation of QGP at the early stage of $A+A$ collision at the CERN SPS energies.

The same conclusion was obtained in Ref. [10]. In the model presented in that paper it was assumed that due to the statistical nature of the creation process the strangeness in the early stage is already in equilibrium and therefore possible secondary processes do not modify its value. As the strangeness to entropy ratio is lower in the QGP than in the confined matter, the *suppression* of strangeness production is expected to occur when crossing the transition energy range from below. The total strangeness production is usually studied using the experimental ratio

$$E_s = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle} , \qquad (2)$$

which measures the ratio of the mean multiplicities of Λ hyperons and $K, \bar{K}$ mesons to the multiplicity of pions. This is an experimental analog of the quantity R_s (1). In Fig. 2 the experimental data of E_s ratio (2) are shown together with its theoretically expected behaviour according to Ref. [10]. The deconfinement phase transition causes a nonmonotonic behaviour of E_s with the collision energy. The maximum of E_s is in the energy region between the AGS and SPS.

III. Charmonium and Open Charm Production

Charmonium production in hadronic [11] and nuclear [12] collisions is usually considered to be composed of three stages: the creation of a $c\bar{c}$ pair, the formation of a bound $c\bar{c}$ state and the subsequent interaction of this $c\bar{c}$ bound state with the surrounding matter. The first process is calculated within perturbative QCD, whereas modeling of non–perturbative dynamics is needed to describe the last two stages (see, e.g., [13] and references therein). The interaction of the bound $c\bar{c}$ state with matter causes suppression of the finally observed charmonium yield relative to the initially created number of bound $c\bar{c}$ states. This initial number is assumed to be proportional to the

number of Drell–Yan lepton pairs, which then allows for the experimental study of the charmonium suppression pattern. It was proposed [14] that the magnitude of the measured suppression in nuclear collisions can be used as a probe of the state of high density matter created at the early stage of the collision. The rapid increase of the suppression (*anomalous suppression*) observed when going from peripheral to central Pb+Pb collisions [15] is often attributed to the formation of the QGP [16].

It was recently found [10, 17] that the mean multiplicity of J/ψ mesons increases proportionally to the mean multiplicity of pions when p+p, p+A and A+A collisions at CERN SPS energies are considered. We illustrate this unexpected experimental fact by reproducing in Fig. 3 the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ as a function of the mean number of nucleons participating in the interaction for inelastic nuclear collisions at the CERN SPS. The $\langle J/\psi \rangle$ and $\langle h^- \rangle$ denote here the mean multiplicities of J/ψ mesons and negatively charged hadrons (more than 90% are π^- mesons), respectively.

In the standard picture of the J/ψ production based on the *hard creation* of $c\bar{c}$ pairs and the subsequent *suppression* of the bound $c\bar{c}$ states the observed scaling behavior of the J/ψ multiplicity appears to be due to an 'accidental' cancelation of several large effects. A very different picture was proposed in Ref. [18] which explains a scaling property of the J/ψ multiplicity

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \cong const(A) \tag{3}$$

by assuming that a dominant fraction of J/ψ mesons is produced directly at hadronization according to the available hadronic phase space. J/ψ mesons are neutral and unflavored, i.e., all charges conserved in the strong interaction (electric charge, baryon number, strangeness and charm) are equal to zero for this particle. Therefore, its production is not influenced by the conservation laws of quantum numbers. Consequently, the J/ψ production can be calculated in the grand canonical approximation and, therefore, its multiplicity is proportional to the volume, V, of the matter at hadronization. Thus, the statistical yield of J/ψ mesons at hadronization is given by

$$\langle J/\psi \rangle = \frac{(2j+1)\,V}{2\pi^2} \int_0^\infty p^2 dp \, \frac{1}{\exp[(p^2 + m_\psi^2)^{1/2}/T_H] \, - \, 1} \tag{4}$$

$$\cong \frac{(2j+1)\,V}{2\pi^2} T_H m_\psi^2 K_2\left(\frac{m_\psi}{T_H}\right) \cong (2j+1)V\left(\frac{m_\psi T_H}{2\pi}\right)^{3/2} \exp\left(-\frac{m_\psi}{T_H}\right) \ ,$$

where $j = 1$ and $m_\psi \cong 3097$ MeV are the spin and the mass of the J/ψ meson and T_H is the hadronization temperature. The previously mentioned results of the analysis of hadron yield systematics in elementary and nuclear collisions within the statistical approach indicate that the hadronization temperature T_H is the same for different colliding systems and collision energies. This reflects the universal feature of the hadronization process.

The total entropy of the produced matter is proportional to its volume. As most of the entropy in the final state is carried by pions, the pion multiplicity is also expected to be proportional to the volume of the hadronizing matter. Thus the scaling property (3) follows directly from the hypothesis of statistical production of J/ψ mesons at hadronization and the universality of the parameter T_H. Since elements of hadronizing matter move in the overall center of mass system the volume V in Eq. (4) characterizes in fact the sum of the proper volumes of all elements in the collision event.

The hypothesis of statistical production of J/ψ mesons at a constant hadronization temperature T_H leads to the prediction of a second scaling property of the J/ψ multiplicity, namely:

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \; \cong \; const(\sqrt{s}) \tag{5}$$

which should be valid for sufficiently large c.m. energies, $\sqrt{s}$. This scaling property is illustrated in Fig. 4 which shows the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ as a function of $\sqrt{s}$ for proton–nucleon interactions. The experimental data on J/ψ yields are taken from a compilation given in [19]. The values of $\langle h^- \rangle$ are calculated using a parameterization of the experimental results as proposed in [20].

Onwards from the CERN SPS energies, $\sqrt{s} \cong 20$ GeV, the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ is approximately constant, in line with the expected scaling behavior (5). The rapid increase of the ratio with collision energy observed below $\sqrt{s} \cong 20$ GeV should be attributed to a significantly larger energy threshold for the J/ψ production than for the pion production. In terms of the statistical approach the effect of strict energy–momentum conservation has to be taken into account by use of the microcanonical formulation of the model.

The statistical J/ψ multiplicity (4) depends on two parameters, T_H and V. However, a simple way to estimate of the crucial temperature parameter in Eq. (4) from the experimental data is possible, provided that we find a

second hadron which has the properties of the J/ψ meson, i.e., it is neutral, unflavored and stable with respect to strong decays. The best candidate is the η meson. The multiplicity of η mesons seems to obey also the scaling properties (3) and (5). The independence of the $\langle\eta\rangle/\langle\pi^0\rangle$ ratio on the collision energy was observed quite a long time ago [21]. Recent data on η production suggest that $\langle\eta\rangle/\langle\pi^0\rangle$ ratio is also independent of the size of the colliding objects. In central Pb+Pb collisions at 158 A GeV the ratio $\langle\eta\rangle/\langle\pi^0\rangle = 0.081 \pm 0.014$ is measured [22]. It is consistent with the values of the ratio reported for all inelastic p+p at 400 GeV [23] (0.077 ± 0.005) and S+S at 200 A·GeV [24] (0.12 ± 0.04). From the measured ratios, $\langle J/\psi\rangle/\langle h^-\rangle$ and $\langle\eta\rangle/\langle\pi^0\rangle$, we estimate a mean ratio $\langle J/\psi\rangle/\langle\eta\rangle = (1.3 \pm 0.3) \cdot 10^{-5}$. Here we use the experimental ratio $\langle\pi^0\rangle/\langle h^-\rangle \cong 1$ in N+N interactions [25]. Under the hypothesis of the statistical production of J/ψ and η mesons at hadronization the measured ratio can be compared to the ratio calculated using Eq. (4):

$$\frac{\langle J/\psi\rangle}{\langle\eta\rangle} \cong \frac{3\ m_\psi^2\ K_2(m_\psi/T_H)}{m_\eta^2\ K_2(m_\eta/T_H)}\ , \tag{6}$$

where $m_\eta \cong 547$ MeV is the mass of the η meson. This leads to an estimate of the hadronization temperature, $T_H \approx 176$ MeV. A graphical solution of Eq. (6) is shown in Fig. 5 which illustrates the high sensitivity of the estimate of the T_H parameter by using the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio. This is due to the large difference between mass of the J/ψ and the η mesons as the right hand side of Eq. (4) is approximately proportional to $\exp[(m_\eta - m_\psi)/T_H]$.

In the proposed model the creation of the J/ψ mesons is due to the straight thermal production at hadronization and not due to the coalescence of $c\bar{c}$ quarks produced before hadronization. Therefore the yield of J/ψ mesons is independent of the production of open charm, which is carried mainly by the D mesons in the final state. The D mesons multiplicity is determined by the number of $c\bar{c}$ quark pairs created in the early *parton stage* before the hadronization. Assuming chemical equilibrium of charm in the QGP stage of A+A collision we can estimate the ratio of the open charm hadrons to pions. The charm to entropy ratio is defined by the quantity

$$R_c \equiv \frac{N_c + N_{\bar{c}}}{S}\ , \tag{7}$$

similar to Eq. (1) for the ratio of strangeness to entropy. The behaviour of R_c (7) for the HG and QGP is shown in Fig. 6 as a function of T for $\mu_B = 0$.

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In Fig. 6 the quantity R_s (1) from Fig. 1 is also presented for a comparison. The behaviour of R_c is completely different from that of R_s. R_c in the QGP is strongly increasing with T and its values are much larger than in the HG. The experimental analog of R_c is $E_c = \langle D \rangle / \langle \pi \rangle$, which measures the ratio of the mean multiplicities of D mesons to the multiplicity of pions. The assumption of the conserved total entropy and the total number of charm quarks and antiquarks during the hadronization of QGP leads then to the picture of chemical non-equilibrium hadron gas at the chemical freeze-out with a strong enhancement of D mesons yield. The ratio of D mesons to pions should strongly increase with the collision energy from the SPS to the RHIC.

IV. Summary

Statistical production of starngeness and charm discussed in this talk can be summarized as the following:

- The transition to the QGP in A+A collisions could be seen as a non-monotonic dependence on collision energy of the strangeness to pion ratio in the energy region between the AGS and the SPS.

- The yield of J/ψ mesons at the CERN SPS can be understood assuming the statistical production of J/ψ at the hadronization, and it is sensitive to the hadronization temperature. The D mesons multiplicity is determined by the number of $c\bar{c}$ quark pairs created in the early QGP stage. The ratio of D mesons to pions is expected to increase strongly with the collision energy from the SPS to the RHIC.

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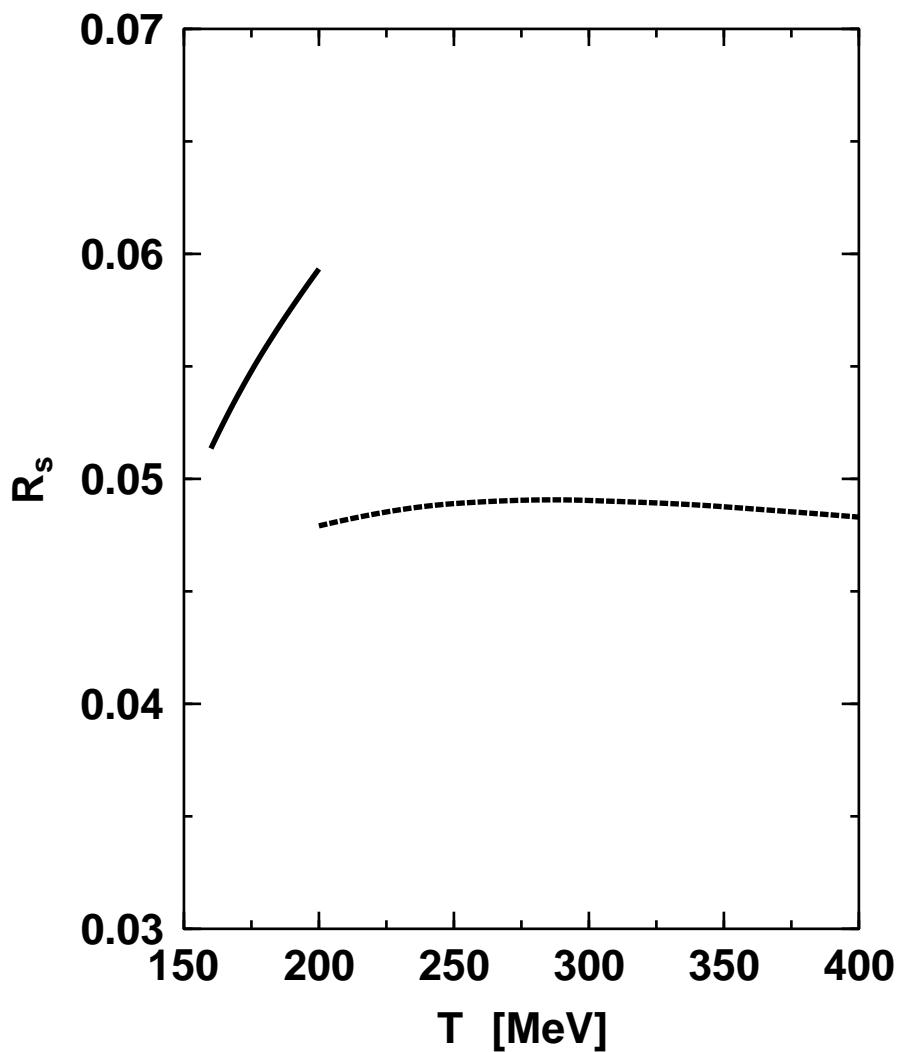
Figure 1: R_s (1) at $\mu_B = 0$ for the HG (solid line) and the QGP (dashed line).
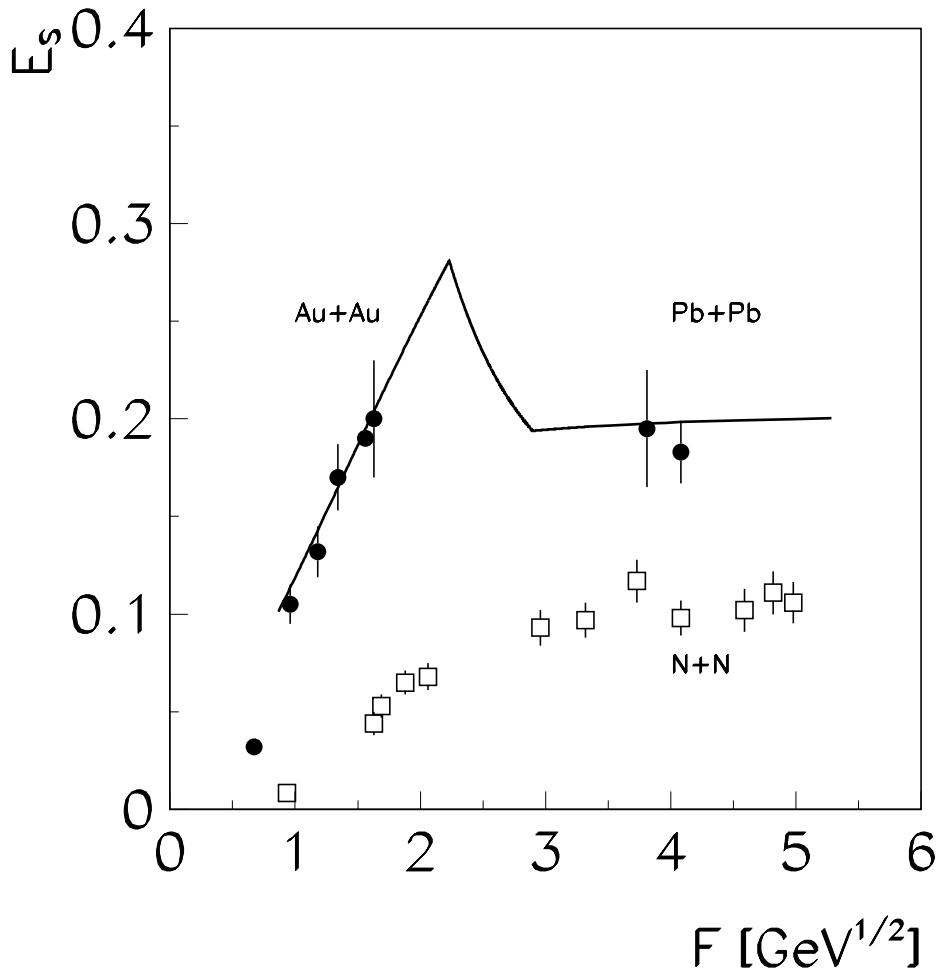
Figure 2: The dependence of the strangeness to pion ratio, E_s (2), for the central A+A collisions (closed circles) and nucleon-nucleon interactions (open squares) as a function of the collision energy measured by the variable $F = (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$. The solid line shows predictions of the statistical model of Ref. [10]. A transition to the QGP takes place between the AGS ($F \approx 2$) and the SPS ($F \approx 4$) energies.
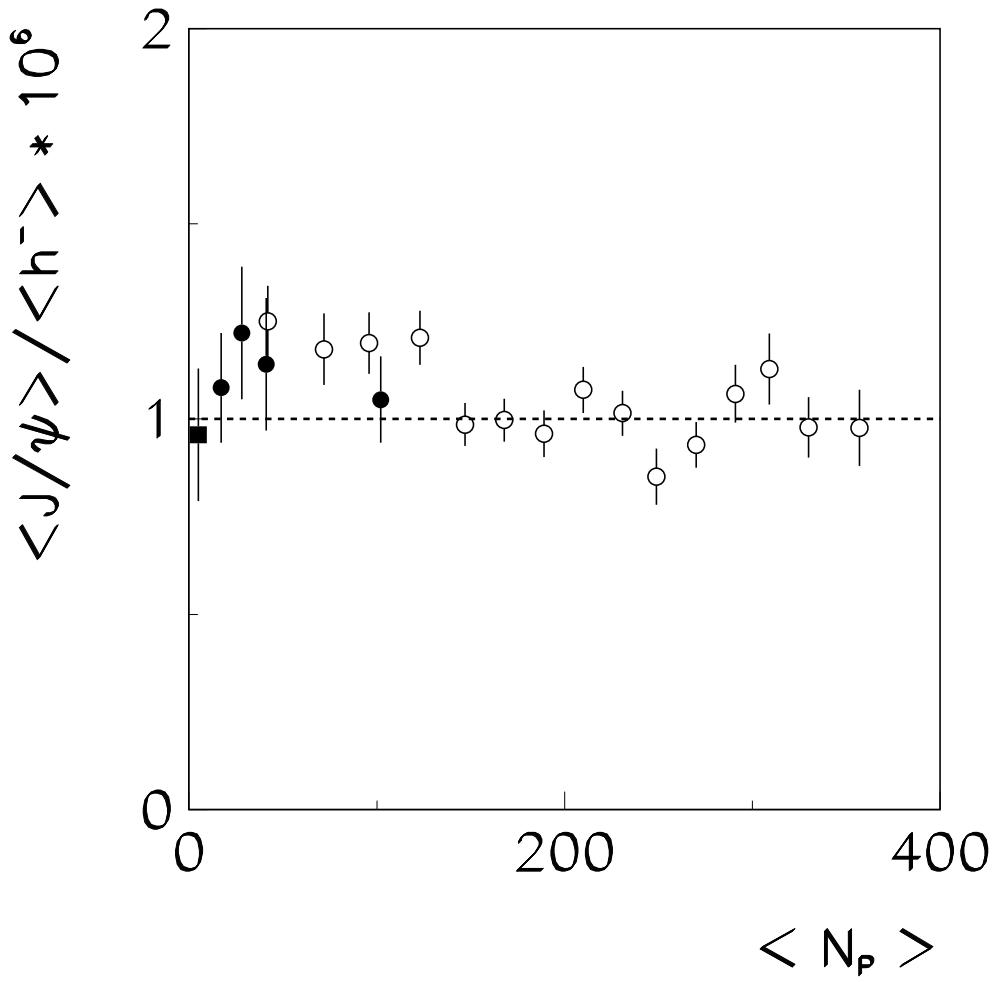
Figure 3: The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A·GeV plotted as a function of the mean number of participant nucleons. The results for Pb+Pb interactions measured for different centralities of collisions are shown by open circles. For clarity the N+N point is shifted from $\langle N_P \rangle = 2$ to $\langle N_P \rangle = 5$. The dashed line indicates the mean value of the ratio.
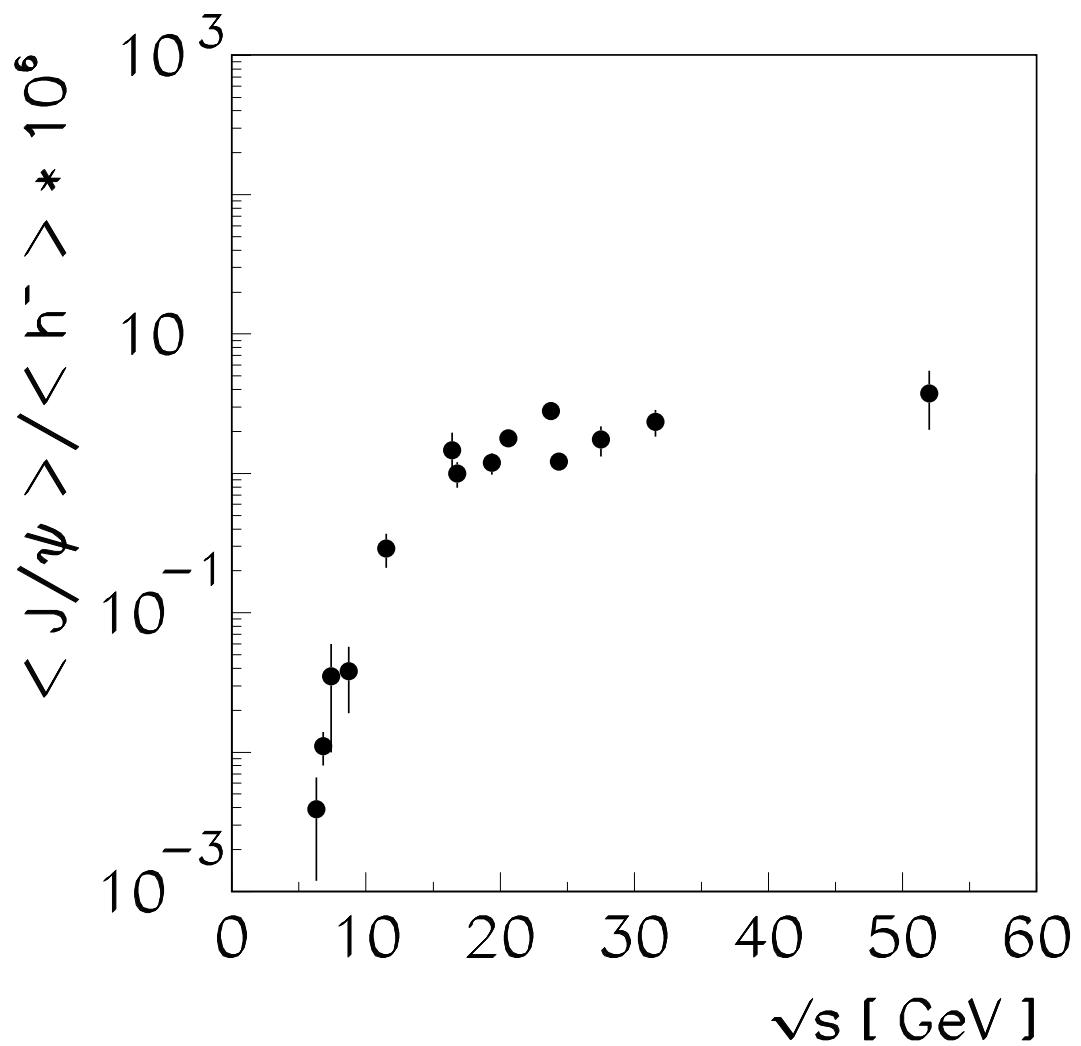
Figure 4: The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic proton–nucleon interactions as a function of the collision energy in the center of mass system.

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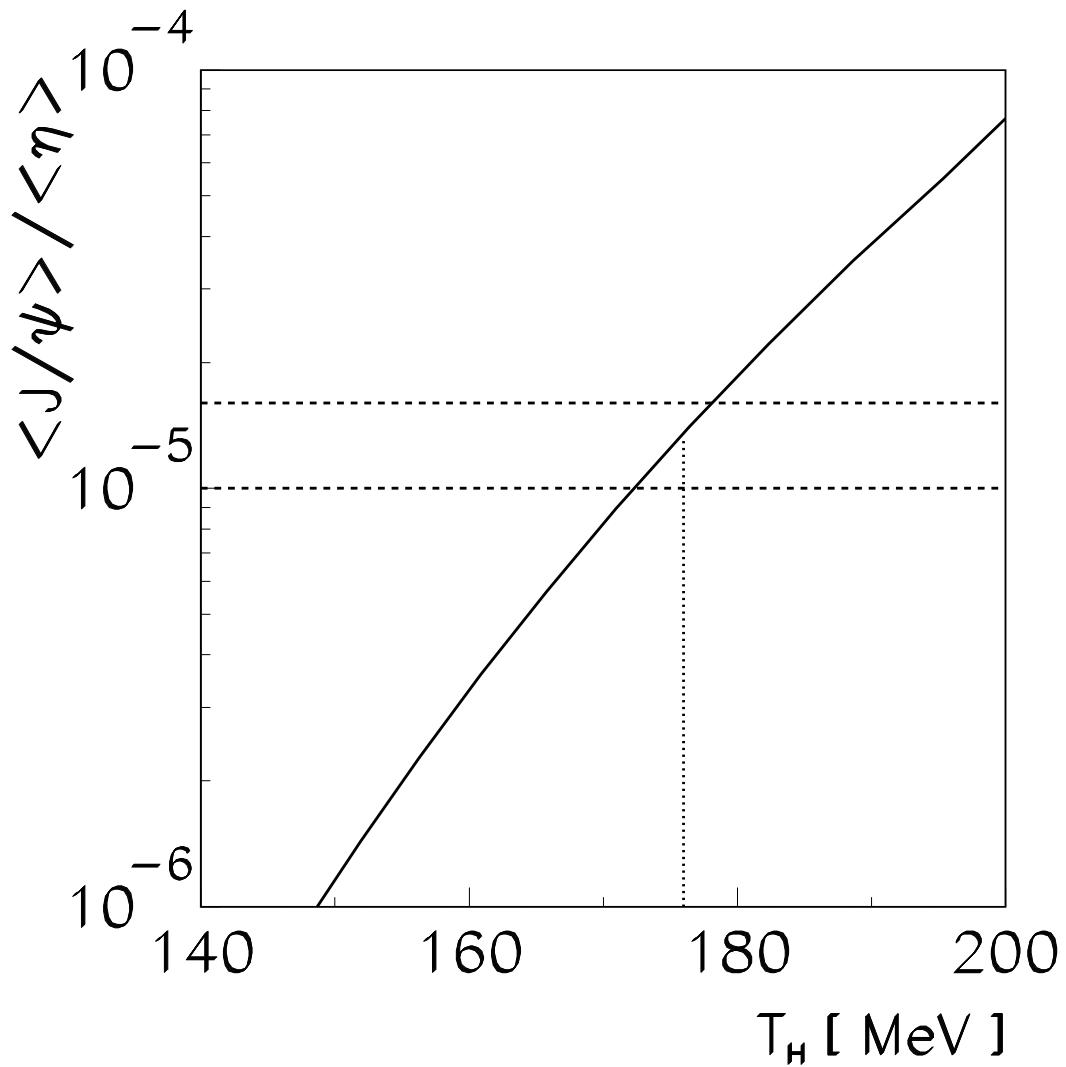
Figure 5: The $\langle J/\psi \rangle / \langle \eta \rangle$ ratio calculated under hypothesis of the statistical production of J/ψ and η mesons at hadronization (solid line) as a function of the hadronization temperature. Band shown by dashed lines is drawn at $\pm\sigma$ around the mean experimental value of the $\langle J/\psi \rangle / \langle \eta \rangle$ ratio. The dotted line indicates $T_H = 176$ MeV.

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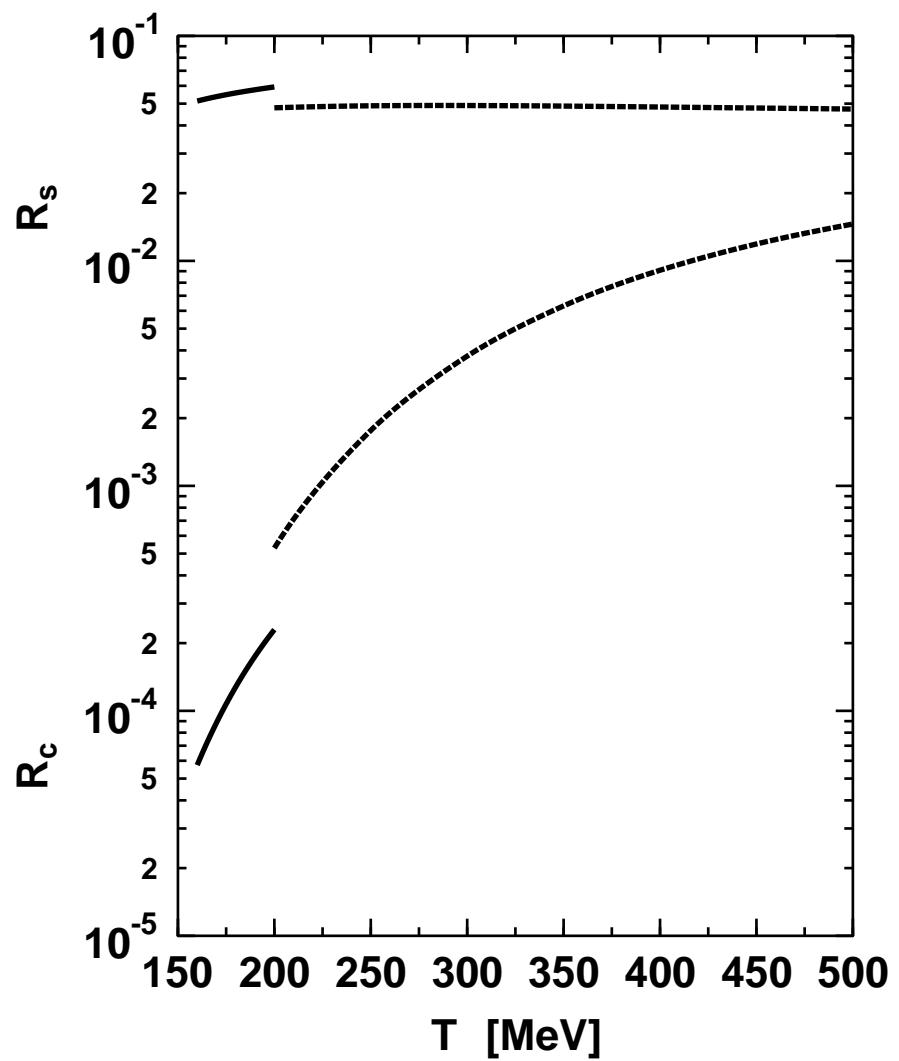
Figure 6: R_c (7) at $\mu_B = 0$ for the HG (solid line) and the QGP (dashed line). R_s behaviour from Fig. 1 is also presented (upper lines) for a comparison.